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Students' views of uncertainty in formal and personal science

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ABSTRACT

Background: Uncertainty is a crucial element of scientific knowledge growth. Students should have some understanding of how science knowledge is developed and why scientific conclusions are considered more or less certain than others. A component of the nature of science, it is considered an important aspect of science education and allows students to recognize the limitations of scientific research.

Purpose: This study examined Grades 5 and 9 students' views of uncertainty in their personal scientific research and the formal scientific research of professionals.

Sample: This study included 33 students in Grade 5 ($n = 17$) and Grade 9 ($n = 16$). The students were recruited from a charter school that emphasised inquiry instruction.

Design and methods: Data were collected through interviews. Students were asked their views of their inquiry-based projects and their views of professional science.

Results: Interview data and statistical analyses indicated that students recognized uncertainty in personal science, which varied across elements of the scientific process. Additionally, their views of uncertainty in formal science tended to change across grades and knowledge of uncertainty in personal and formal science were positively correlated.

Conclusion: These findings offer insights into the processes by which students come to understand uncertainty in science and point to ways of fostering such knowledge through teaching practices.

KEYWORDS

Science; uncertainty in science; inquiry; development; epistemology

Throughout their adult lives, students will have to make judgements about their trust in science (Roberts et al. 2013). Although a substantial amount of scientific knowledge is accepted as true and universal (e.g. the law of gravity), other knowledge is considered less certain and our current understanding may change over time (e.g. human evolution and migration). To make scientific judgements, students need some understanding of how science knowledge has been established, under what circumstances knowledge is considered reliable and how knowledge is generally agreed upon (Carey and Smith

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1993). Hence, an understanding of the nature of science is considered an essential part of science education, as it ensures that students appreciate the limitations of scientific knowledge claims and helps them critically examine the products of science and technology (Khishfe 2012).

The nature of science literature has a sound research foundation and can be traced back to the general area of personal epistemology (Perry 1970). *Personal epistemology* is the study of 'beliefs that individuals hold about knowledge and knowing' (Hofer 2006, 1). Perry (1970) posited that individuals pass through a sequence of epistemological understanding. Subsequently, several distinguished researchers have used similar frameworks to probe adolescent and adults' views of the nature of knowledge, its source, and justification (e.g. King and Kitchener 1994). On the whole, consensus exists concerning the course of epistemological development (Hofer and Pintrich 1997), which can be divided into three main positions or levels of understanding. At the first level, individuals start out with a fact-based epistemology for thinking about knowledge claims in their everyday life. Knowledge is thought of as a collection of facts conveyed to the layperson by experts. Disparity of opinion between experts is either not recognized or assumed to vary because of inadequate knowledge. Differences between experts are resolved when all the facts are known or when everyone looks at the facts in an unbiased manner. At the second level, individuals begin to recognize a diversity of views and uncertainty in knowledge. Alternative viewpoints are accepted equally, however, without discriminating between them or weighing evidence. In other words, everyone has a right to an opinion. At this level, individuals still maintain that experts who disagree have not yet found the right answer and the truth is yet to be found. At the third and final level, individuals acknowledge that uncertainty is a hallmark of seeking knowledge; it is impossible to know the absolute truth because knowledge is relative and changing. Disparity of opinion between experts is accepted; knowledge is formed from weighing and justifying available evidence. Consequently, theories of the world change as new evidence emerges. Research on personal epistemology has demonstrated that most individuals function at the first level (knowledge as fact and unchanging) during childhood and begin to move to the second and third levels in later adolescence and adulthood (Conley et al. 2004; Mansfield and Clinchy 2002).

Studies have applied the progression of personal epistemology to understanding of the nature of scientific knowledge (e.g. Carey and Smith 1993; Hofer and Pintrich 1997). To illustrate, in a series of studies Carey and colleagues (Carey et al. 1989; Carey and Smith 1993) identified three levels similar to Perry (1970) based on answers to questions about the science conducted by professional scientists (i.e. formal science), including the role of ideas, model makers, and testing. Like the findings on personal epistemology, students generally stayed at a Level 1 until they reached adolescence. As individuals move through the three levels identified by Carey and colleagues, they become increasingly aware of the complexity of the scientific process and how scientific knowledge changes and develops. This movement toward understanding *uncertainty in science* is an important component of the nature of science. Similar to personal epistemology, when individuals truly comprehend that the process of science can be uncertain (i.e. at Level 3), they also recognize that controversies in science do not negate science as a process or the knowledge subsequently gained. Instead, they see the importance of reasoned argument in evaluating competing claims and that debate among scientists is a part of

the process of knowledge formation (Smith et al. 2000). The literature on uncertainty in science has indicated that most children and young adolescents do not hold this position and instead a large proportion continue to believe that how we come to form scientific knowledge is a certain, clear-cut process (Akerson and Volrich 2006).

Factors that impact understanding of uncertainty in science

Scientific researchers and practitioners recognize that uncertainty in science yields knowledge change and such change occurs over time. Researchers have argued that growth in scientific knowledge and potential theory change transpires because of (a) advances in our thinking and technology, which allows new evidence to emerge that challenges our previous theories; (b) the subjectivity of the scientist, which can lead to a re-evaluation of conclusions drawn from data; and (c) the interchange among experts, which can lead to changes in how the theories of science are viewed (Lederman, Antink, and Bartos 2014). With this in mind, science educators and researchers of science education have puzzled over how pedagogy can support students' to develop an understanding of the nature of science, including understanding the function of uncertainty in scientific knowledge change (Manz 2015).

Pedagogy

Several educational researchers have advocated that students can be helped to understand uncertainty in science and the role it plays in knowledge growth and theory change by placing less emphasis on students' views of the activities of professional scientists (i.e. formal science) and more on how students perceive their own scientific inquiry practices (i.e. personal science; Sandoval 2005). *Inquiry* is a teaching approach where students pursue a question, research it, and generate a conclusion (Khishfe and Abd-El-Khalick 2002), thereby, following the path taken by professional scientists in their formal scientific research but doing so within their own science projects (i.e. personal science). The *National Science Education Standards* document claimed that 'engaging students in inquiry helps students develop ... an appreciation for 'how we know' what we know in science, understanding of the nature of science [and] skills necessary to become independent inquirers about the natural world' (National Research Council 1996, 105).

Proponents of inquiry have argued that when students experience the process of science as authentic, they acquire a deeper understanding of how scientific knowledge is developed, shared, and used by the scientific community (Furtak et al. 2012). That is, students develop their personal views of uncertainty in science as they engage in their own science activities (Sandoval 2005). By experiencing the messiness of science, students see places within the scientific process that can lead to uncertainty in their findings and, if uncertainty is present in their personal science activities, they might also perceive the formal activities of professional scientists as potentially containing uncertainty (Sandoval 2005), or at least recognize it as feasible when teachers brings it forward for discussion. To date, however, little research exists that specifies the relation between understanding uncertainty in personal and formal science. Instead, the general trend in the literature appears to be that students do not make a link between the two

(e.g. Yaboubian and BouJaoude 2010). Further, critics of inquiry argue that such claims about the benefits of inquiry have been unsubstantiated experimentally (Furtak et al. 2012). For instance, inquiry-based instruction programs have been shown to improve achievement (Nwagbo 2006), but it is not clear that they have promoted a better understanding of tenets of nature of science including uncertainty (Khishfe and Abd-El-Khalick 2002; Sandoval 2005). To illustrate, after an inquiry-based instruction unit with sixth graders, Khishfe and Abd-El-Khalick (2002) found that 52% of the participants articulated informed views of the tentative nature of formal science, but only when they spent time reflecting on the process. In another study, Yacoubian and BouJaoude (2010) assessed students' views of the nature of science, including uncertainty in inquiry-based laboratory activities, and found no substantial improvement when knowledge was measured by an open-ended questionnaire at pre- and post-test.

Two possible limitations of the studies conducted to date, which might account for the inconsistent findings, include the duration of the inquiry-based programs (i.e. many have lasted only a few weeks to two or three months) and the way in which the inquiry program was presented (i.e. as a supplement in conjunction with traditional instruction rather than as a comprehensive program that replaced the traditional approach). In other words, some studies involving inquiry have not have been long enough, coherent enough, and consistent enough to support a change in views of nature of science (Akerson and Volrich 2006; Khishfe and Abd-El-Khalick 2002). Support for these arguments is suggested in a study conducted by Smith et al. (2000) who found that sixth grade students, who were in an inquiry classroom over a period of 6 years, held more informed views in areas of the nature of science (e.g. empirical testing, collaboration with colleagues, creating explanations, and developing scientific ideas), as compared to students from a traditional classroom setting. Although the study did not ask direct questions about uncertainty in science, the findings support the claim that young students are able to develop in some facets of the nature of science as conducted by professional scientists.

Another concern voiced in the literature is that although a percentage of students recognize that uncertainty plays some role in the scientific process, for an unknown reason their beliefs continue to be superficial (Sandoval 2005). That is, students report uncertainty about evidence as due to lack of information on the part of scientists (i.e. one scientist is right because he/she has the information whereas another is wrong because he/she does not have the necessary information), but typically do not acknowledge it is possible to hold different interpretations of data (Bell et al. 2003). Thus, there is a need for further research into the potential influence of inquiry-based activities on knowledge of uncertainty in personal science (Khishfe and Abd-El-Khalick 2002) and the way that knowledge might be aligned or misaligned with beliefs about uncertainty in formal science (Sandoval 2005). These factors in the extant literature led us to formulate the following research questions.

Research questions

- (1) Following Metz (2004), Smith et al. (2000), and Akerson and Volrich (2006) we asked: Is there is a developmental progression in the views of uncertainty in

science (personal and formal) of Grades 5 and 9 students who experienced an inquiry-based pedagogy?

- (2) Following Sandoval (2005), we asked: Is there a positive relationship between students' capacity to identify uncertainty in personal and formal science?

Methods

Data collection

Description of school

Following ethics approval, students were recruited from a charter school in a large urban centre in Western Canada. In Canada, education is the responsibility of provinces so the structure of charter schools differs nationally across the 10 provinces and 3 territories. Within the province in which this study was conducted, charter schools are publicly-funded, non-profit schools that follow the mandated provincial curriculum. Unlike traditional schools, however, they aim to meet the needs of a particular group of students through a specific program or teaching and/or learning approach (e.g. arts, music, and science). A special interest group advocating for a charter school must approach the local school board and obtain the school board's support for the school. The school board then applies to the Ministry of Education, providing a rationale for how the program to be offered is significantly different from the programs offered by the existing school board. If approved, the charter school is treated like other public schools. Students living within the school's jurisdiction are given first priority for enrolment, with remaining applicants accepted on a first come, first-serve basis. The charter school in this study served students in Grades 4 to 9. It distinguished itself from other schools by adopting an inquiry-based approach to instruction and offering an enriched program infused with science, mathematics, and technology.

Teacher participants

One female Grade 5 teacher and two male Grade 9 teachers participated in the study. To confirm pedagogical fidelity, teachers were interviewed about how they used inquiry in their classrooms and were observed during two science periods. It was confirmed that the teachers implemented an inquiry-based pedagogical approach in their classrooms, as described by the National Research Council (1996).

Student participants

A total of 33 students in Grade 5 ($n = 17$, 12 boys, 5 girls; mean age 10 years, 9 months) and Grade 9 ($n = 16$, 8 boys, 8 girls; mean age 14 years, 8 months) participated. These grades were selected to examine developmental change because research has suggested there is a progression from childhood to adolescence in personal and scientific epistemology (Mansfield and Clinchy 2002). Students enter the school in Grade 4; therefore, at the time of data collection, students in Grade 5 had experienced inquiry-based learning for over one year and the Grade 9 students for more than 5 years.

Student interview and coding

A semi-structured interview format was used to inquire into students' understanding of uncertainty in science. We used two interview protocols that focused on (a) students' own science activities (i.e. personal science) and (b) those of professional scientists (i.e. formal science). The personal science protocol (Metz 2004) was administered first, followed by the formal science protocol (Metz 2004; Songer and Linn 1991). In what follows, the interview protocols and scoring procedures are described.

Personal science interview protocol

Following Metz (2004), our aim was to deduce if students could identify what made the knowledge they generated through their own scientific experiments subject to uncertainty (Appendix A lists the interview questions). Specifically, questions explored students' uncertainty regarding experimental design (Categories 1, 2, and 3), generalizability of the findings (Category 4) and the theory accounted for by the trend

Table 1. Number and percentage of students who identified each category and source of uncertainty.

Category of uncertainty	Source of uncertainty	Students	
		Grade 5 (n = 17)	Grade 9 (n = 16)
1. How to produce desired outcome due to a lack of knowledge		1 (6)	9 (56)**
2. Data as uncertain			
	Possible instrument error due to poorly calibrated instruments	14 (82)	12 (75)
	Experimenter error or experimenter unreliability, due to: a) moments of inattentiveness, b) experimenter's perceptual limitations, c) use of imprecise measurement technique, and d) human interference with organisms under study	9 (53)	10 (63)
		10 (59)	5 (31)
3. Trend identified in the data.			
	Experimental procedure: a) lab conditions fail to simulate 'nature conditions,' b) weakness in experimental set-up, c) possibility of more adequate test of comparison under study	17 (100)	15 (93)
		4 (24)	12 (75)***
	Patterns in the data: a) perceived conflict of data with prior observations, b) perceived conflict with theory-based expectations, c) not sufficiently robust differences in the data to support attribution of causality	6 (35)	1 (6)*
	Insufficient data: a) data collection procedure too short, b) too few organisms/participants, c) study run too few times, c) only one group studied, e) study run under inadequate number of experimental conditions, f) organisms/participants run only once each, g) idiosyncrasies of individuals studied	17 (100)	8 (50)***
	Research design: a) possible order effect, b) failure to control all factors but the one under investigation, c) experimental confound	11 (65)	5 (31)
4. Generalizability of the trend.			
	Limited range of experimental conditions tested.	7 (41)	4 (25)
	Possible organism/sample variability.	0	2 (13)
		7 (41)	2 (13)
5. Theory that best accounts for the trend		6 (35)	5 (31)

* $p < .05$, ** $p < .01$, *** $p < .001$.

in data (Category 5) (See Table 1). For example, when asked how sure they were of their findings, students may identify some uncertainty in the accuracy of their data because of possible measurement error (Category 2). Nine of the students, five in Grade 5 and four in Grade 9, were interviewed about experiments they had conducted as part of their school science fair. The remaining students were interviewed, using the same questions, regarding a class experiment they had conducted. Both sets of activities were classified as personal science.

Three of the five categories identified by Metz (2004) were broken down into sub-categories, namely *sources* of uncertainty (see Table 1). To illustrate, *data as uncertain* contained the sources: instrument error and experimenter error. Examples from students' response protocols are provided in the results section to show how they reasoned their way toward the categories and sources of uncertainty.

Formal science interview protocols

Following Metz (2004) and Songer and Linn (1991), our aim was to explore how students construed the nature of formal scientific knowledge and the role of uncertainty in its creation. This second interview protocol consisted of the following three general questions about the activities of professional scientists and, as such, were different from the preceding set that focused on the students' experiments.

- (1) If a scientist found different results than you, can only one result be right or can both be right?
- (2) Can scientists look at the same experiment and reach different conclusions?
- (3) To check their findings, do scientists compare their results to those of others?

In line with the stages of personal epistemology, responses were coded as Levels 1, 2, or 3 (Carey and Smith 1993; Kuhn et al. 2008) for each question. At Level 1, knowledge is viewed as a collection of clear-cut facts disseminated by experts. At Level 2, there is recognition that multiple opinions can exist and at Level 3, the complexity of knowledge formation through argumentation and the potential of resulting new research findings is acknowledged. A score of 0 was recorded when students gave answers that suggested they did not understand the question (range from 0 to 9).

Interrater reliability'

A second coder independently analyzed 25% of the interviews that were randomly selected from each grade. Interrater reliability for uncertainty in personal science was high with a Cohen's kappa coefficient of .88 for category coding and .87 for source coding (Landis and Koch 1977). Interrater reliability for uncertainty in formal science was also high with a Cohen's kappa coefficient of .83. The few differences that emerged were resolved by consensus based on further consultation on the response.

Results

We first present 'h' quantitative results to answer research question one in an effort to identify potential developmental differences between Grades 5 and 9 students. Next, examples of Grades 5 and 9 student responses to interview questions are offered to

highlight how they viewed scientific uncertainty in personal science (i.e. their own science activities) and in formal science (i.e. professional scientists' activities). Pseudonyms are used for illustrative quotations to maintain confidentiality. Question two is addressed next through a correlational analysis of students' total number of categories of uncertainty identified in their personal science activities and their total scores on formal science questions.

Students' views of uncertainty in personal science

The first step in the analysis involved determining if different performance patterns were evident when students were questioned about individual experiments versus classroom experiments. T-tests indicated that there were no significant differences in uncertainty scores between students who conducted their own science experiment and students who engaged in the classroom-wide experiment, $ps > .05$. Thus, the two types of personal science activities were combined as one.

To determine if there was a developmental progression in the Grades 5 and 9 students' views of uncertainty in personal science, chi-square analyses compared the frequency with which students in both grades identified categories of uncertainty in their science activities (identified in Table 1). Analyses found grade differences in the frequency of identification in Category 1: *How to produce the desired outcome*. A greater percentage of ninth graders (56%) identified this category in their experiments than fifth graders (6%), $\chi^2(1, 32) = 6.44, p = .01, \Phi = .08$.

No grade differences were found for Category 2: *Data as uncertain*. Nor were there grade differences for the two sources of uncertainty. A similar number of students in each grade identified possible error due to the instruments used for measurement or experimenter unreliability.

For Category 3: *Trend identified in the data*, there were no grade differences at the category level. Within the category, grade differences were observed for three sources. A greater percentage of ninth graders (75%) identified *experimental procedure* as a source of uncertainty than fifth graders (24%), $\chi^2(1, 32) = 8.74, p = .001, \Phi = .09$. A greater percentage of fifth graders (35%) identified *patterns in the data*, than ninth graders (6%), $\chi^2(1, 32) = 4.16, p = .04, \Phi = .06$. More fifth graders (100%) than ninth graders (50%) also identified *insufficient data* as a source of uncertainty in their experiments, $\chi^2(1, 32) = 11.22, p = .001, \Phi = .10$.

No grade differences were observed for Category 4: *Generalizability of the trend* and Category 5: *Theory that best accounts for the trend*. Nor was there a grade difference for the source of uncertainty within Category 4, which identified possible error due to a limited range of experimental conditions tested.

Overall, some categories and sources of uncertainty were identified more often by one or another of the grades, but there was not a general trend toward a greater proportion of Grade 9 students identifying uncertainty in the majority of categories. In both grades, students recognized at least one out of five *categories* of uncertainty, and 59% of fifth graders and 69% of ninth graders conceptualized three or more categories of uncertainty. Figure 1 shows the percentage of students in each grade who identified a category of uncertainty. The *trend identified in the data* was the category of uncertainty acknowledged most often, followed by *data as uncertain*. Of the five categories of

Figure 1. Percentage of grade 5 and 9 students' identification of categories of uncertainty.

uncertainty, all 17 fifth graders and 15 of the 16 ninth graders identified the *trend in the data* as uncertain. For sources of uncertainty within the categories, all of the Grade 5 students identified insufficient data as one source of uncertainty ($n = 17$); fewer students identified concerns about the experimental procedure ($n = 4$), research design ($n = 11$), and patterns observed in the data ($n = 6$). In comparison, for the ninth graders, concerns with the experimental procedure was the most commonly cited source of uncertainty ($n = 15$) followed by insufficient data ($n = 8$), research design ($n = 5$), and patterns in the data ($n = 1$).

Qualitative examples of Grade 5 views of uncertainty in personal science

To illustrate how Grade 5 students articulated the uncertainty they felt toward their science activities, we have selected excerpts from the interviews. The excerpts represent the kind of responses we received from students, but the number are limited due to space constraints. The following is one example from a typical student's discussion of her research. We refer to her as Jamie (pseudonym assigned). 'We were trying to find out if the wetland was healthy or not. And we concluded that it was healthy but there was- the phosphate levels are just a little bit higher.' When asked, 'How sure are you of your findings?' Jamie suggested that although her group had strictly adhered to their tests procedures ('My group is pretty sure because we did the tests and we followed them like exactly.'), they were not entirely certain if the results were robust because of insufficient data:

... I wondered if we went back like a couple of weeks later or like even every weekend if we did it and the test results came up surer. Then I suppose that it would be correct ... We could have tested other wetlands to see if they had the same amount or any areas like that or maybe you can look in books to see.

As a strategy to address her perception of uncertainty Jamie suggested replication of tests across multiple student groups simultaneously and successively: 'If all of the groups did all of the tests at once, or even at different times, and then we all came up with the

same results or different, we could figure out why.’ She also suggested observations of the flora and fauna that indicate wetland health:

Or we could also all go on a hike around ... It might have helped because there were a whole bunch of intolerant species, but there were a whole bunch of tolerant species, and stuff. So maybe if we looked around and found a whole bunch of plants that are usually around wetlands or maybe deer or anything. We did actually see one [a deer]!’

Qualitative examples of Grade 9 views of uncertainty in personal science

Unlike many fifth graders, ninth graders were significantly more concerned about the experimental procedure they developed to gather data. The following excerpts from Juan’s (pseudonym assigned) interview demonstrate the back-and-forth thought process that occurred as he struggled to express the experimental procedure he used and the uncertainty inherent in it. When asked by the Investigator what he did for his oil sand project, Juan explained how to produce a desired outcome by first planning the procedure to be used in the study and then testing it to identify flaws: ‘What we did – we had a bucket of oil sand. We had to write a procedure beforehand. Then after we tested our procedure a bit we’d find out why it was horribly flawed and kind of edited it.’ Juan then evaluated the specific procedure he used, deemed it a failure, and thought of an alternate procedure: ‘Mine involved shaking it and I realized that wouldn’t work at all and I just switched to (pouring) boiling water through it.’ In response to the question, ‘Why did shaking not work?’ he explained:

Because the oil- the oil is pretty much – I don’t know the term – but it stuck to the sand and it needs, like – heat gives it – activity, or, I don’t know the terms. But it makes it easier to get it off the sand.

His evaluation of the procedure suggested limited success: ‘Then after a while some of the oil started to rise to the top, then we started draining it and we got some more oil.’ When asked, ‘How pleased were you with the final results?’ he again voiced uncertainty in his procedure’s capacity to produce the desired outcome: ‘Not too pleased because we didn’t get much, but really no one got much.’

Students’ views of uncertainty in formal science

Views of uncertainty in formal science were coded according to three levels (See [Appendix B](#) for the coding for each questions and illustrative responses from interviews; Carey and Smith 1993). Grade 5 and Grade 9 students’ patterns of responding to the formal science questions, displayed in [Table 2](#), were examined using a chi-square analysis to determine possible grade differences on each of the three questions posed

Table 2. Percentage of grade 5 and 9 students’ responses to the uncertainty in formal science interview according to epistemological level.

Level	Question 1			Question 2			Question 3		
	1	2	3	1	2	3	1	2	3
Grade 5	88	0	12	88	6	6	59	24	18
Grade 9	56	44	0	31	63	0	44	50	6

to the students. Significant grade differences were found on questions 1 and 2. For both questions more ninth graders provided answers at Level 2 than fifth graders, $\chi^2(2, 31) = 10.48, p = .01, \Phi = .10$; 2, $\chi^2(2, 30) = 13.29, p = .00, \Phi = .11$.

Qualitative examples of Grade 5 views of uncertainty in formal science

A majority of Grade 5 students provided responses about the formal activities of professional scientists that represented views at Level 1 (see Table 2). At Level 1, students talk about ideas as either right or wrong and knowledge as a collection of facts. When differences are observed between experts, it is because one expert is wrong or biased, or does not have all the facts. To illustrate Ari, a typical fifth grader was asked, 'Can scientists can reach different conclusions from the same experiment?' Ari's response suggested that differences are due to a mistake by one of the scientists rather than acknowledging there is uncertainty in the interpretation of data: 'Maybe somebody made a mistake or they might have done something different than the other person by a mistake or they didn't follow the instructions.' His idea that a scientist would follow instructions suggests he sees scientific activities as a clear-cut and lacking uncertainty. When asked if two scientists did the experiment together but disagreed on the interpretation of data, he maintained that there had to be different experimental conditions: 'It might be at a different time of the day, but if they did it at the exact same time, like collected the water at the exact same time, they probably made a small mistake that might have caused it to be off.' By insisting there was a difference in the experiment or one scientist made a mistake, Ari is emphasizing the idea that there is one right conclusion and alternate conclusions are due to error rather than differences in interpretation.

A minority of Grade 5 students provided responses at a Level 3. The idea of weighing evidence when there are differing interpretations characterizes a Level 3 response. Because there is uncertainty in knowledge formation, scientists form conclusions through debate and the available evidence. In the following, Cynthia (Grade 5) identified the importance of sharing ideas to advance scientific knowledge:

Two brains [are] way better than one, and if we share our opinions, you tell your answer that you got, you can totally do it again. You can get other, like, advice on (from) other scientists on how to deal with it. And if you have a problem and you are stuck, they can probably deal with that too.

When asked why it was important to collaborate, she initially explored the idea of one scientist being wrong but then approached the notion of debate to reduce uncertainty: 'They are completely different, so they probably have different opinions on everything... But if they did it in the same area and one person did it wrong and one person said it was bad, then there should actually be a debate.'

Grade 9 views of uncertainty in formal science

Although some Grade 9 students responded to the interview questions about formal science at a Level 1, approximately half provide answers at a Level 2 across the three questions. At Level 2, students acknowledge differences in scientists' views but still maintain that there is a correct answer or one study is more accurate than another. To illustrate, when a Grade 9 student, Celia, was asked if scientists can look at the same

experiment and have diverse conclusions, she admitted the individual perspectives of scientists could lead them to interpret the results of a study in different ways: 'If you have bias on something ... you can look at one piece of data and see one thing or another person can look at another piece of data and see another.'

Uncertainty in personal vs. formal science

To answer research question 2, we used correlation coefficients to assess the relation between views of uncertainty in personal science and formal science. For each student, scores for personal science were given for the total number of categories of uncertainty identified (out of 5). Scores for formal science were calculated by totalling the scores that each student received for the three questions (out of 9). There was a significant positive correlation between the number of categories of uncertainty identified in personal science and scores for uncertainty in formal science, $r(32) = .38$, $p = .03$.

Discussion

Developing students' views of the nature of science, including uncertainty in science, has been an ongoing focus of education for decades (e.g. National Research Council, 1996). Inquiry has been proposed as a teaching practice that can promote nature of science understanding. Proponents of inquiry have claimed that through the act of doing authentic science, students will develop a greater appreciation for how science knowledge develops and changes. Although students' inquiry practice shares features with professional science, the extant literature has consistently shown that students in inquiry-based programs continue to hold naïve views of nature of science (e.g. Lederman 1992). One problematic feature in the literature involves how students' understanding of nature of science has been assessed. Standardized rating scales have largely focused on the formal activities of scientists (e.g. Views of Nature of Science Questionnaire; Lederman et al. 2002). Little research has focussed on understanding the ideas students hold about personal science and determining if their ideas have a developmental trajectory that changes in tandem with views about formal science (Carey et al. 1993; Metz 2004). Sandoval (2005) called for greater emphasis on understanding the epistemological beliefs that students bring to their science activities and how their views can be used to support them in developing a sophisticated understanding of nature of science.

This study investigated how students conceptualized uncertainty in their own experiments as well as their understanding of uncertainty in the activities of professional scientists. We aimed to determine if developmental differences in students' understanding of uncertainty in science existed across Grades 5 and 9 students in each area (i.e. personal and formal science) and if there was a relationship between students' understanding in the two spheres.

Personal science

Our analysis did not reveal a statistically significant overall developmental difference in students' views of uncertainty in personal science from Grade 5 to Grade 9, as measured

by their identification of Metz's (2004) five categories of uncertainty. All categories were identified by at least one student in each grade; and 59% of fifth graders and 69% of ninth graders identified at least three categories of uncertainty. Additionally, close to 90% of these students were able to suggest a reasonable strategy for reducing their uncertainty. This finding indicates that, even the Grade 5 students understand that uncertainty is part of the scientific process and that they are at least somewhat able to name and describe the uncertainty they experience in their personal science activities. This outcome is noteworthy given the lack of research evidence pointing to students' knowledge of the scientific uncertainty in formal activities scientists (Akerson and Volrich 2006).

The frequency with which students in each grade identified uncertainty in personal science activities differed by category. As shown in Table 1, there was a significant difference in grade performance in one of the five categories of uncertainty, namely *how to produce desired outcome due to a lack of knowledge*. Here, grade nine students outperformed Grade 5 students, which suggests a developmental difference in the two groups' awareness of what they need to know but do not know, and the impact that condition has on the outcomes of their personal science activities. Such metacognitive thought lead our student, Juan, who was quoted earlier, to articulate a way to reduce his uncertainty, including working with other students to discuss a procedure to eliminate flaws ('maybe by doing a group discussion beforehand... then like, if you have a flaw that you don't think is obvious and people do think is obvious they can correct you... I worked by myself, like work with a group so that, instead of just talking ahead of time, working with someone else who has ideas that can like change as you go along.'). This final comment suggests an emerging understanding that knowledge is a growing thing rather than a series of static facts.

When sources of uncertainty were examined, however, there was no obvious developmental trend. Sources of uncertainty differed significantly only for the category 'trend identified in the data.' Statistical analyses showed that fifth graders outperformed ninth graders on two sources of uncertainty, namely patterns in the data (e.g. perceived conflict of data with prior observations, perceived conflict with theory-based expectations, and not sufficiently robust differences in the data to support attribution of causality) and insufficient data (e.g. data collection procedure too short, too few organisms/participants, and study run too few times). In contrast, Grade 9 students outperformed Grade 5 students on one source, namely *experimental procedure*. To illustrate, a greater proportion of ninth graders expressed uncertainty about the method they choose to extract oil from the sand mixture (how to produce the desired outcome). In general, they more frequently noted their method was less successful due to the constraints of their instruments than the fifth graders. During their interviews, some ninth graders recognized the need to try a different approach and evaluated the potential success of a new method. That these fifth and ninth grade students were able to consider these factors demonstrates a developing understanding of the nature of science.

In spite of these specific developmental differences, however, the absence of an overall developmental trend from Grades 5 to 9 might suggest that the measurement of scientific uncertainty is affected by the content of the personal science activities. For example, in the oil sand study, the type of inquiry activity conducted by students may

have influenced the type of uncertainty identified. In other words, because the experiments differed in design, different components of the scientific process might be seen as having greater uncertainty than others. Nevertheless, the ability of students in both grades to identify areas of uncertainty in their activities adds to our knowledge of how using authentic science activities can help students understand what scientific uncertainty is, as demonstrated in participants' discussion of Metz's (2004) categories and sources of uncertainty. Additionally, such activities seemingly enable them to respond to the uncertainties they perceive in that many articulated ways to address the uncertainty thereby improving their studies. The two processes of identifying and responding to scientific uncertainty suggest the formation of a basis for building a working knowledge of how scientific knowledge grows and changes.

Formal science

Students' responses to the questions about formal science exhibited developmental progression on two of the three questions posed. A greater proportion of ninth graders fell at a Level 2 whereas more fifth graders fell at Level 1. That is, compared to fifth graders, a greater proportion of ninth graders understood that scientists who hold different views can both be somewhat right and wrong as conclusions are influenced by one's perspective. In contrast, more fifth graders held that there is one correct conclusion and difference were due to errors in procedure. Very few participants reached Level 3 where differing viewpoints can both have merit and evidence must be weighed to judge which is superior. This finding, although tentative due to the limited data set, speaks positively of the developmental growth occurring across grades and is consistent with previous research, which has shown change from childhood to adolescence (e.g. Carey et al. 1989). It also supports previous findings that students in middle and high school continue to hold naïve views of uncertainty in formal science even when they have experienced authentic inquiry activities (Lederman et al. 2014). Moreover, taken together with previous research, the present response pattern provides a developmental roadmap for teachers to follow. As a first step, teachers can help students become aware of their understanding by (a) assessing students' level of understanding, (b) helping students develop a language to describe what they think, and (c) solidifying their knowledge group discussions (Case and McKeough 1990). Second, teachers can scaffold students to the next level through discussions of how knowledge has changed through time and as a result of scientific experiments that often failed and only sometimes succeeded.

The relationship between personal and formal science

Our second research question compared students' views of uncertainty in personal and formal science. A positive correlation between views of scientific uncertainty in the two domains suggests that the better students were at identifying uncertainty in their personal activities, the better they were at understanding the complexities of uncertainty in the formal science conducted by scientists. This correlational analysis offers responds to Sandoval's (2005) call to have students to reflect on the uncertainty in their own science activities and to compare their efforts and challenges to those of professional scientists. Our

findings suggest that when students reflect on their experiments they appear to be able to look at their data and consider a different interpretation, as evidenced by their identification of categories and sources of uncertainty. Speculating on such hypothetical alternative processes might ready them to examine the activities of professional scientists in terms of how (a) their experiments also contain elements of uncertainty, and processes, such as replication of findings, can resolve uncertainties, which challenges the idea of an absolute truth and leads toward an understanding of knowledge as changing and growing. Through this process, students might be further challenged to refine the way they discuss the scientific process and, in so doing, allow knowledge in both the personal and formal scientific domains to interact and form in conjunction. In this way, students receive the support they need to explicitly voice their views and reflect on how uncertainty affected science activities (Khishfe and Abd-El-Khalick 2002; Overoye and Storm 2015).

Potentially, engaging in inquiry activities that aim to simulate understanding of the scientific process can, thus, be a contributing factor to students perceiving a relationship between uncertainty in personal and professional science. However, simply engaging in inquiry without explicit discussion is unlikely to substantially change already established views of students. Hsu, van Eijch and Roth (2010) argued that previous conceptions of science must be challenged and made salient to students through reflection in conjunction with inquiry. Students need the opportunity to make sense of the uncertainty they encountered in their own experiments and how their personal science is related to professional science (Yacoubian and BouJaoude 2010). If students at a Levels 1 or 2 in formal science see scientists' activities as more straightforward but can identify sources of uncertainty in their own activities, they could see their own activities as automatically inferior (Salter and Atkins 2014). When they experience uncertainty in their own learning activities, students have been found to ignore or deny it whereas others choose to take action or reflect on it (Jordan 2015). Differing responses to uncertainty may affect how students learn and engage in science activities and should, therefore, be addressed in science teaching. To mitigate such responses, students' experience of uncertainty in their personal science activities can be juxtaposed with a critical analysis of historical scientific work. When students see how scientists have to manage uncertainty in the scientific process, teachers can identify similarities in the personal activities of students.

We suggest that this study holds important implications for science educators. Primarily, we posit that educators would benefit from considering the views of students as they engage in science activities. As teachers strive to reach curricular objectives, variations in students' conceptual understanding, interest, and motivation often prove challenging. The developmental nature of conceptual understanding in science can provide teachers with a roadmap for how to objectives by highlighting sub-goals and thus supporting instructional differentiation. Such differentiation has been shown to stimulate academic performance, motivation, and interest (Guay, Roy, and Valois 2017). Secondly, the more authentic classroom activities are, the messier and less structured; consequently, it is likely student will identify areas of uncertainty in their activities. Educators can attend to how children respond to uncertainty in personal science and use their responses to broaden the discussion about how knowledge is established through the scientific process. Comparing and contrasting personal and professional science activities through discussion and examples may help students appreciate the challenges of the scientific process and be critical consumers of science and technology.

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Appendix A: Interview questions for personal science (Metz 2004)

In the following, the question(s) asked are listed first followed by the category of uncertainty most likely to be elicited from the questions. There was not always one-to-one correspondence between the questions asked and the category because not all students recognized limitations in come categories or identified a category by expanding on a previous answer.

- (1) Conceptualization of the question researched and methods:
Question: 'Can you tell me about your study?'
(a) If additional prompting was needed: 'What question did you ask? How did you research it? What was your method?'
Category: How to produce the desired outcome
- (2) Conceptualization of research outcomes and level of confidence:
Question: 'What did you find out?' 'How sure are you that [there was a difference in phosphate levels in your water sample]?'
(a) If additional prompting was needed: 'Are you not sure, kind of sure, or really sure?'
Category: Theory that best accounts for the trend
- (3) Possibility of increasing confidence level:
Question: 'Is there a way you could be surer?' 'How would that help you be surer?' 'Any other way? How would that help you be surer?'
Category: Data as uncertain and Trend identified in the data
- (4) Study improvements:
Question: 'When scientists finish a study, they frequently try to figure out how they could have improved their study. You did a good study! Can you think of a way that would make your study a better study?' 'Why would that make your study better?' 'How else could you change your study to make it even better? Why would that make your study better?'
Category: Data as uncertain and Trend identified in the data
- (5) Conceptualization of the generalizability of research findings:
Question: 'I wanted to ask you another question about the study you just did. Do you think your results tell you just about the [health of the wetland at the time] you studied it or [the wetland at different times of the year] as well? Why do you think that [you would need to study the wetland at different times of the year]?'
(a) Weak scaffold if students does not think their findings generalize: 'Is there as way you could set up your study so that it would tell you not just about the [wetland at the time] you studied it, but other times of the year as well? Would that help you learn about [the health of the wetland]? Why? Why not?'
(b) Stronger scaffold if needed: 'Would it help if you studied the wetland throughout the year? Would that help you learn about [the health of the wetland] Why, Why not?'
Category: Generalizability of the trend

Appendix B: Coding Scheme for Uncertainty in Formal Science by Question

Question 1: If a scientist found different results than you, can only one result be right or can both be right?

Level	Example
1. The scientist is right. Conflicting evidence is due to differences in procedure. Students still assume that there is a right answer.	R: If you didn't keep the test exactly the same, then you could get different answers. I: What if they kept it the exact same? R: Then I would think that probably somebody did a mistake somewhere.
2. Both can be right. Both have some error. Knowledge is filtered through a person's perceptions.	R: It's like you can't really- in science you never really prove anything...but all in all everything has something to it that is right.
3. Both can have merit, but there needs to be a weighing of evidence to determine which one is better or makes more sense.	R: A scientists could have said that this wetland was bad and we could have said that it was good. So, both results could be good unless somebody debated it out and they gave us proof.
Question 2: Can scientists look at the same experiment and reach different conclusions?	
1. The procedure should be the same; therefore, the conclusion will be the same. Differences are due to a difference in procedure or uncontrolled error.	R: He might have done a different test... depending on a day when it is rainy or a day it is sunny that can change the temperature.
2. There are different perspectives, and therefore, different interpretations of the data. However, one study is closer to the truth than the other, mainly because of accuracy.	R: ...for example if you had bias on something you can look at one piece of data and see one thing or another person can look at another piece of data and see another.
3. Yes, because of different perspectives, and interpretations. There needs to be dialogue to determine which is better.	R: They are completely different, so they probably have different opinions on everything...But if they did it in the same area and one person did it wrong and one person said it was bad, then there should actually be a debate.
Question 3: To check their findings, do scientists compare their results to those of others?	
1. Compare to find right answer- usually by the number of people who find the same thing. Outliers are discredited, or the scientist with more experience is more credible (scientist as expert). Differences due to error.	R: if another person done it and they got an answer completely different than yours, either one of you are making a mistake, both of you are making a mistake or something happened.
2. Share ideas to increase knowledge. No one right idea, all have merit. Can improve upon own research	R: So, there could be 6 different people doing the exact same experiment and getting the exact same conclusions and no one is sharing it. Sharing ideas or trying to make it better.
3. Acknowledge scientists think differently. Share ideas to reach understanding through discussion and debate	R: I think they would cause if they found this one test, they might ask someone else if they did the same test but got different results. And they might ask them why they got that or why they thought they got that result.